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ORIGINAL ARTICLE

Development of low-carbon recycled aggregate concrete using carbonation treatment and alccofine

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Abstract Since the construction industry is one of the major sectors responsible for the overexploitation of natural resources and the production of greenhouse gases, there is an urgent need to adopt a sustainable and environmental friendly approach to mitigate climate degradation. Research has explored the potential of recycled aggregate (RA) as a viable alternative to natural aggregate in concrete production. Currently, several treatment methods are being employed to enhance the efficient incorporation of RA into concrete, aiming to address this issue. However, the effective utilization of RA in place of NA remains uncommon. In this study, an effort has been made to develop a low-carbon recycled aggregate concrete by utilizing 100% carbonation treated recycled coarse concrete aggregate (CRCCA) in place of natural coarse aggregate (NCA) and alccofine as mineral admixture. A comprehensive analysis was performed, comparing the properties of CRCCA to those of untreated recycled coarse concrete aggregate. This analysis covered changes in weight, bulk density, water absorption, crushing value, and microstructure. Furthermore, five different concrete mixes were prepared, each varying in the proportion of natural coarse aggregate (NCA), untreated RCCA, and CRCCA. These mixes also incorporated alccofine as a mineral admixture. The evaluation process involved assessing the effectiveness of carbonation treatment and alccofine addition through tests on the workability, water absorption, density, and compressive strength of the concrete mixes. The study demonstrated that carbonation treatment of RCCA resulted in substantial improvements in crushing value and water absorption of CRCCA, alongside enhanced workability, reduced water absorption, and increased density in CRCCA concrete. Moreover, CRCCA concrete exhibited notable compressive strength gains at both 28 and 90 days compared to untreated RCCA concrete. Furthermore, the use of CRCCA and alccofine contributed to reducing GHG emissions associated with cement production, emphasizing the environmentally friendly attributes of this low-carbon concrete formulation.

Keywords Low-carbon concrete · Eco-friendly concrete · Carbonated recycled aggregate · Alccofine

1 Introduction

Considered one of the most waste-intensive industries, the construction sector produces vast construction and demolition (C&D) waste (Katerusha 2022). Interestingly, this waste can resolve the problem of diminishing natural reserves and the rising demand for building materials, thus reducing the gap between demand and supply (Ouyang et al. 2023). It is essential to check on resource utilization and waste generation to achieve a sustainable development model; the global resource data have seen a 13-fold rise in resource extraction from 1900 to 2015, giving rise to 89 Gt from 7 Gt. On the other hand, solid waste generation rose from 0.5 Mt. per day to 3.5 Mt. per day from 1900 to 2010 and is expected to double by 2025 (Zhang et al. 2022). The incorporation and encouragement of the utilization of recycled concrete within the construction sector are essential in promoting sustainable construction practices (Katerusha 2021a, b). Many researchers are working on the effective use of recycled aggregate (RA) in concrete (de Andrade Salgado and de Andrade Silva 2022); as a result,

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some countries have already started promoting RA in various construction activities (Safiuddin et al. 2013). However, the consumption of RA in concrete is still restricted due to various shortcomings of RA relative to natural aggregate (NA). In assessment, concrete containing RA possesses inferior mechanical and durability characteristics compared to NA concrete (Shi et al. 2016; Kisku et al. 2017). Low-density, high-water absorption, increased porosity, and less mechanical strength are some significant factors associated with RA. Past research shows that the properties of RA can be improved in two ways: by removing the attached old mortar or by strengthening the microstructure.

In an endeavor to increase the utilization of RA in concrete, many treatment methods have been introduced, such as surface modification (Shayan and Xu 2003; Tsujino et al. 2007), acid treatment (Tam et al. 2007), ultrasonic cleaning treatment (Katz 2004), mechanical crushing and impact treatment (Nagataki et al. 2004; Quattrone et al. 2014), heat treatment (Akbarnezhad et al. 2011; Quattrone et al. 2014), multiple stage mixing technique using admixtures (Tam and Tam 2008). Studies have shown that these treatment methods have their advantages and disadvantages (Pu et al. 2021). Mechanical grinding of RA offers operational simplicity, efficient removal of poorly attached mortar, and improved ITZ formation but produces low-quality materials, induces microcracks, and demands precise equipment (Kasai 2006; Shi et al. 2016). Heating treatment of RA reduces adhered mortar pore size, minimizes ITZ cracks, and enhances the new ITZ but involves high energy consumption, higher cost, generates low-value fine material and is prone to micro-crack formation (Akbarnezhad et al. 2011; Wang et al. 2019). Ultrasonic cleaning of RA enhances the new ITZ and compressive strength but is energy-intensive, expensive, generates low-quality materials, and struggles with strongly adhered mortar (Shi et al. 2016). Pre-soaking in acid reduces mortar pore size, minimizes ITZ cracks, and enhances the new ITZ while absorbing CO_2, yet it generates harmful waste solutions, decreases RA's pH, and increases the risk of chloride and sulfate content (Al-Bayati et al. 2016; Wang et al. 2017). The use of pozzolanic materials enhances mortar on RAs, reducing waste, densifying the microstructure, and improving recycled aggregate concrete (RAC) performance (Li et al. 2009, 2017; Kou and Poon 2012). Polymer emulsion strengthens mortar on RAs, reduces porosity, densifies RAs, and improves water absorption but generates waste, potentially negatively affecting compressive strength, is time-intensive, and incurs high costs (Kou and Poon 2010; Spaeth and Djerbi Tegguer 2013). Calcium Carbonate bio-deposition improves recycled concrete aggregate (RCA) quality, RAC strength, and new ITZ but lowers RCA pH and requires strict and challenging-to-control test conditions (Qiu et al. 2014; Zeng et al. 2019).

In recent studies, many researchers have used accelerated carbonation technique to enhance the characteristics of recycled coarse concrete aggregate (RCCA) and utilize the CO_2 to benefit the environment (Thiery et al. 2013; Kou et al. 2014; Zhan et al. 2014; Jiake et al. 2015). As per a study (Monkman and Shao 2010), 1 ton of cement attached to RCCA can utilize about 0.5 tons of CO_2. The accelerated carbonation treatment of recycled aggregates presents numerous other benefits, including easy operation, cost-effectiveness, densification of ITZ, enhanced performance of RAC, and diminished carbon dioxide emissions. It does, however, pose some minor drawbacks, such as an increase in the number of small pores (Pu et al. 2021), which can be mitigated through the use of fine supplementary cementitious material (SCM). As the CO_2 possesses more hardness and solid phase in comparison with $Ca(OH)_2$, the CO_2 reacts with the hydration products $Ca(OH)_2$, C–S–H, AFt, and AFm to produce $CaCO_3$ (Jiake et al. 2015), which increases the density as well as fills the cracks that further improves the characteristics of carbonated recycled coarse concrete aggregate (CRCCA) in comparison with untreated recycled coarse concrete aggregate (UTRCCA) (Xuan et al. 2016; Russo and Lollini 2022). The improvement in water absorption, frost resistance, and porosity is more noticeable in a dry atmosphere in comparison with a humid atmosphere (Gholizadeh-Vayghan et al. 2020). After the carbonation of RCCA, the solid weight of treated RCCA may increase by 11–23% (Fernández Bertos et al. 2004; Jiake et al. 2015). Many studies have shown improvement in the water absorption, density, and crushing value of RCCA following carbonation treatment (Pu et al. 2021). The water absorption and apparent density of carbonated RCCA were reported to improve by 30 and 4.8%, respectively (Lu et al. 2019). The enhancement in the properties of CRCCA can be attributed to the compactness of the microstructure of RCCA due to $CaCO_3$ deposition during carbonation treatment (Russo and Lollini 2022).

Out of all the treatment techniques and methods for effective utilization of RCCA in concrete, pozzolanic materials can be considered one of the most practical methods, which consumes less time and energy (Muduli and Mukharjee 2020). The existence of silica fume in RCCA concrete can enhance the pozzolanic activity owing to the enhancement in the properties of the mix (Corinaldesi and Moriconi 2009; Kou et al. 2011; Radonjanin et al. 2013). The addition of ground granulated blast-furnace slag (GGBS), nanoparticles, fly ash (Zheng et al. 2021), and metakaolin (Yaba et al. 2021) was also seen to improve the microstructure, mechanical and durability characteristics of RCCA concrete (Corinaldesi and Moriconi 2009; Kou et al. 2011; Tung et al. 2023; Wang et al.

2023). Similarly, alccofine is also a new kind of mineral additive that has been proven to enhance the characteristics of geopolymer concrete (Jindal 2019). Alccofine is a fine microparticle with a particle size of 4–6 microns attained from the leftovers of the iron ore industry (Jariwala et al. 2016). Alccofine, whose principal constituents are SiO_2, Al_2O_3, CaO, and MgO, significantly enhances the hydration of concrete mix. Distinguished by its ultra-fine particle size and advantageous chemical composition, alccofine sets itself apart from other pozzolanic materials. By enhancing the hydration, packing density, permeability, strength, and durability properties of concrete, alccofine confers a unique set of properties.

As per the latest published literature, limited research has been conducted to analyze the outcome of adding alccofine and RA in concrete. Karthik and Nagaraju (2023) investigated the workability and strength properties of the concrete cast with the replacement of NA with RA and partial replacement of cement with 25% fly ash and alccofine in various ratios. Santhoshkumar and Saravanan (2022) investigated the strength and microstructure properties of recycled aggregate concrete (RAC) including M-Sand, river sand, and alccofine using three approaches, that is, surface coated aggregate, two-stage mixing approach, and double mixing method. Sakthivel and Jagadeesan (2022) investigated the flexural strength, crack pattern, and ductility of the beams and columns cast with RA and alccofine. Jasani et al. (2018) investigated concrete's strength and durability properties by incorporating RA and alccofine. Due to the extensive range of potential approaches in evaluating and enhancing the characteristics of RAC incorporating alccofine, arriving at a definitive conclusion with the existing limited research becomes difficult.

Taking into consideration the above-mentioned points, previous research has not explored the impact of carbonated RCCA in combination with alccofine with the aim of enhancing the quality of recycled aggregate concrete. As explained above, carbonating RCCA introduces a drawback by increasing the presence of small pores. However, these pores can be effectively sealed by the ultra-fine particles of alccofine, leading to improvements in the microstructure of the resulting concrete. In this study, alccofine was selected over other mineral admixtures due to its ultra-fine microparticles and its advantageous chemical composition, encompassing all four essential components: SiO_2, Al_2O_3, CaO, and MgO. Additionally, the use of alccofine can help reduce the reliance on cement, even in high-quality concrete mixes. Furthermore, as alccofine is derived from industrial waste, the author attempts to present an environmentally friendly approach for the efficient utilization of RCCA in concrete, aligning with the principles of sustainable development. This research involves a comprehensive investigation, including SEM and EDX analysis of the microstructure of RCCA, the characterization of RCCA properties before and after treatment, and the assessment of various properties of concrete prepared with natural aggregate, untreated RCCA, and RCCA treated in the presence of alccofine.

Table 1 Physical properties and chemical composition of various materials

Parameters	OPC	Alccofine
SiO_2 (%)	19.24	35.23
Al_2O_3 (%)	6.78	22.12
CaO (%)	68.50	32.84
Fe_2O_3 (%)	–	0.95
SO_3 (%)	–	0.15
MgO (%)	4.66	6.33
K_2O (%)	0.48	–
Specific gravity	3.15	2.70

2 Materials and methods

2.1 Raw material

The current investigation used 43-grade ordinary Portland cement (OPC) with a specific gravity of 3.15. The maximum size of RCCA used was 12.5 mm and was used by crushing old concrete from C&D waste. Both coarse aggregates use a similar range of particle size. The specific gravity of untreated RCCA (UTRCCA) and the natural aggregate was observed as 2.45 and 2.65, respectively. The current study used a commercially available alccofine with a specific gravity of 2.7 and an average particle size range of 4–6 microns. The physical and chemical composition of OPC and alccofine can be seen in Table 1. The alccofine comprises four primary chemical components: SiO_2, CaO, Al_2O_3, and MgO. The existence of these components contributes impressively to the enhancement of hydration reactions. The ultra-fineness and favorable chemical composition of alccofine facilitate the formation of cementitious gel, leading to improved permeability, density, strength, and durability of the concrete. Alccofine can improve the strength and durability characteristics of the mix and decrease the amount of cement required due to its higher hydration activity. The SEM analysis of alccofine, as per Fig. 1, reveals the particles' uneven shape and ultra-fine size. Commercially available river sand was used in all the concrete mixes for fine aggregate. Regular tap water was used for all the concrete mixes.

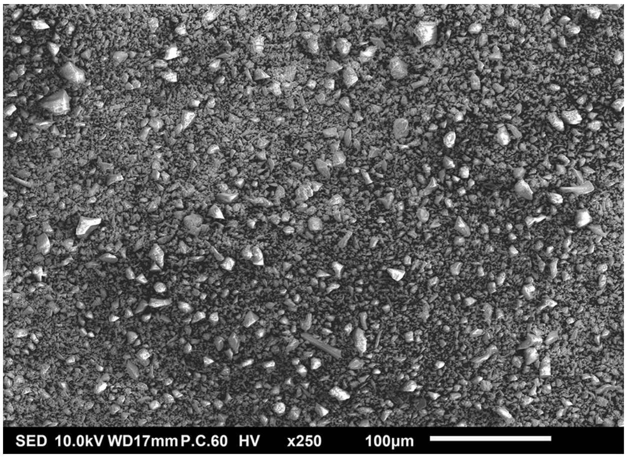

Fig. 1 SEM image of alccofine

2.2 Carbonation treatment

During the accelerated carbonation treatment of RCCA, CO_2 is introduced into RCCA, which reacts with the free water present in the pores, forming H_2CO_3—the ionizing of H_2CO_3 results in the generation of H^+, HCO_3^-, CO_3^{2-} ions. The CO_3^{2-} ions further react with the calcium ions produced by the decomposition of C–S–H, $Ca(OH)_2$, C_2S, C_3S, and Af_t to produce $CaCO_3$ (Fernández Bertos et al. 2004; Phung et al. 2015; Pu et al. 2021). The carbonation treatment process of RCCA is illustrated in Fig. 2 for better understanding. This study used a carbonation treatment apparatus containing an airtight steel carbonation chamber and a CO_2 cylinder. The carbonation chamber was initially vacuumed before injecting pure CO_2 gas. The RCCAs were then treated for 72 h with a CO_2 concentration of 20% and relative humidity of 60 ± 5% at a temperature of 28 °C. The process was repeated until enough carbonation treated RCCA (CRCCA) was obtained.

2.3 Concrete mix

The concrete mix design containing 100% NA was prepared as per BIS 10262 (2009). Five different concrete mixes with varying coarse aggregates that are: 100% NA (NAC); 50% untreated RCCA and 50% NA (UTRCCA50); 50% carbonation treated RCCA and 50% NA (CRCCA50); 100% untreated RCCA (UTRCCA100); and 100% carbonation treated RCCA (CRCCA100) were made. All the concrete mixes were produced with alccofine. Table 2 represents the composition of various concrete mixes. To prepare the mixes, saturated surface dry (SSD) RCCA and NA were used.

2.4 Testing

All the treated RCCA were analyzed and related to the properties of untreated RCCA. The treated RCCA were examined for change in weight, water absorption, bulk density, crushing value, and microstructure. The workability of treated and untreated RCCA concrete mix was evaluated through a slump test of a freshly made concrete mixture as per BIS 1199 (1959). Concrete cubes of 150 mm from all the mixes were made to determine the concrete's water absorption and compressive strength. The 28 days water absorption for concrete samples was evaluated as per ASTM C642 (2013). The compressive strength of concrete for 7, 28, 56, and 90 days was evaluated as per BIS 516 (2004). A flowchart of testing the properties of RCCA and various RCCA concrete mixes can be seen in Fig. 3. The final reading was taken as the average of 3 samples. The environmental aspect of the concrete cast with RCCA and alccofine was also discussed.

3 Results

3.1 Effect of carbonation treatment on various properties of RCCA

The water absorption capacity of the RA depends on the volume of pores and the volume of old mortar attached to the RA, which can significantly affect various properties of the concrete (Lockrey et al. 2016). As per the observation of change in weight after carbonation treatment, the weight of CRCCA increased by 18% compared to the weight of

Table 2 Concrete mix proportions

Samples	Cementations material (kg/m^3)	Cement (kg/m^3)	Alccofine (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Natural coarse aggregate (NCA) kg/m^3	Recycled coarse concrete aggregate (RCCA) (kg/m^3)	Superplasticizer % of cement	W/C ratio
NAC	561	421	140	204	715	893	–	1.7	0.31
UTRCCA50	561	421	140	204	715	450	416	1.7	0.31
UTRCCA100	561	421	140	204	715	–	826	1.7	0.31
CRCCA50	561	421	140	204	715	450	416	1.7	0.31
CRCCA100	561	421	140	204	715	–	826	1.7	0.31

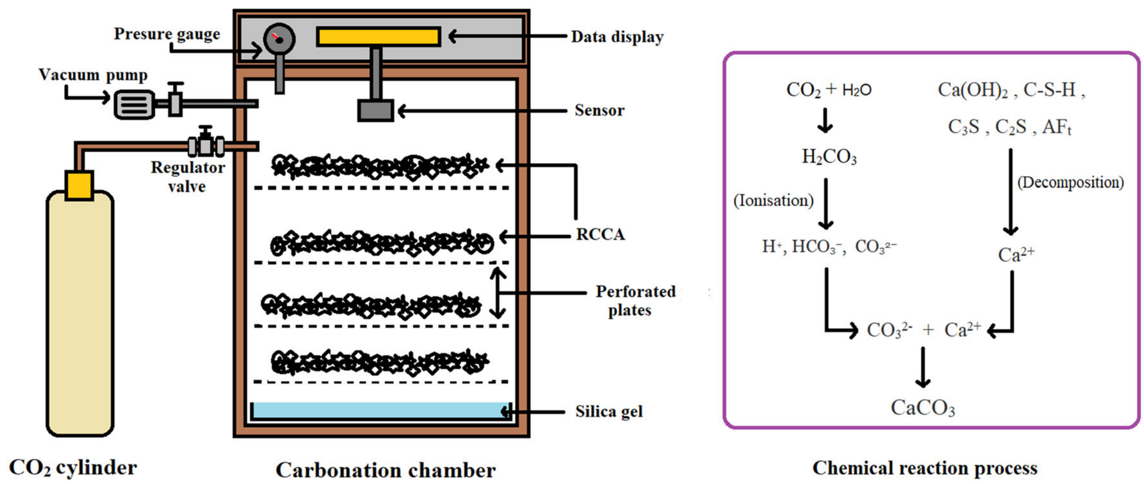

Fig. 2 Carbonation treatment process of RCCA

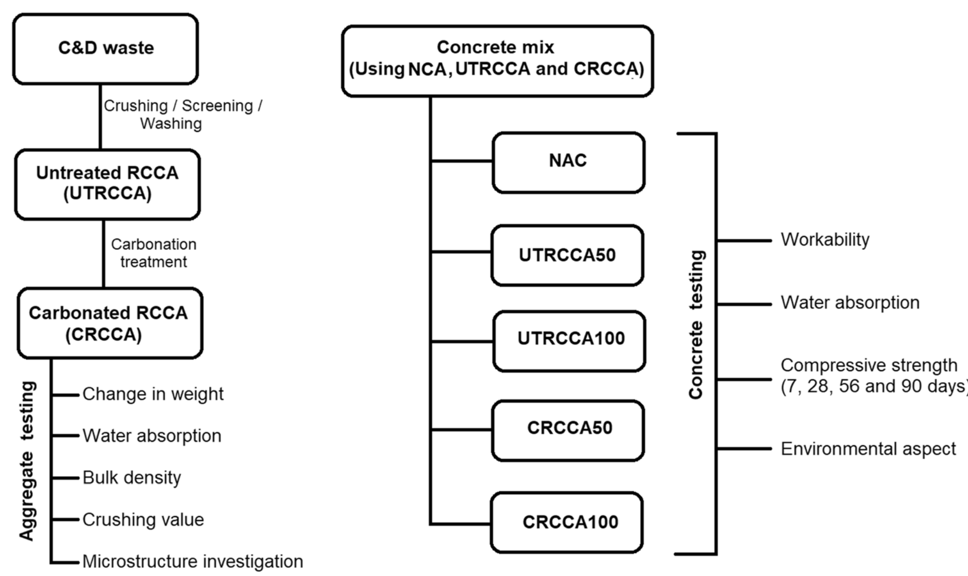

Fig. 3 Flowchart of aggregate and concrete testing

UTRCCA. The water absorption of CRCCA was found to be 18% less in comparison with the water absorption of UTRCCA. A slight improvement of 4% in the bulk density of CRCCA relative to UTRCCA was found after the treatment. Similarly, the crushing value of CRCCA was 23% lower than UTRCCA's. Previous studies also obtained similar results (Lu et al. 2019). The improvements in the properties of the CRCCA were due to the compact microstructure and decreased porosity due to the creation of $CaCO_3$ and silica gel (Lu et al. 2018). This can further be confirmed by the SEM and EDX analysis of UTRCCA and CRCCA. Figure 4a and b demonstrates the SEM images of UTRCCA and CRCCA, respectively. Several cracks can be observed as per the SEM analysis of UTRCCA, which are closely related to the degraded properties of UTRCCA. Instead, as per the SEM image of CRCCA, a dense structure with fewer pores can be observed, which may be responsible for the improved properties of CRCCA. The element composition through EDX analysis of UTRCCA and CRCCA can be observed in Fig. 5a and b. The significant difference in Fig. 5a and b is the increased carbon content. The UTRCCA possesses 3% carbon content, whereas CRCCA contains 18.67% carbon content, which verifies the effectiveness of the carbonation treatment on RCCA.

3.2 Properties of RCCA concrete

Figure 6 shows the workability of various concrete mixes with respect to slump value. It can be analyzed from the results that the slump value of the concrete mixes UTRCCA50 and UTRCCA100 increased in comparison with NAC. The slump value of the controlled mix, NAC, was 160 mm whereas the slump values of UTRCCA50 and

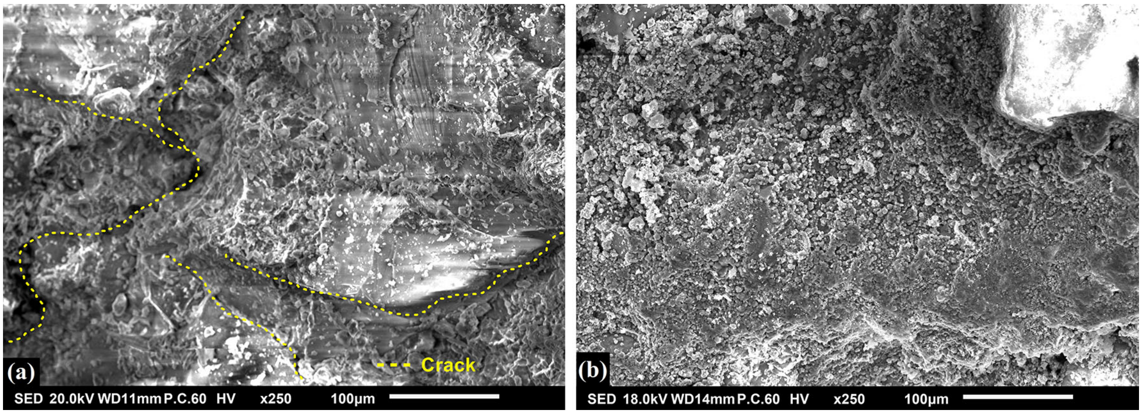

Fig. 4 SEM images: (**a**) UTRCCA; (**b**) CRCCA

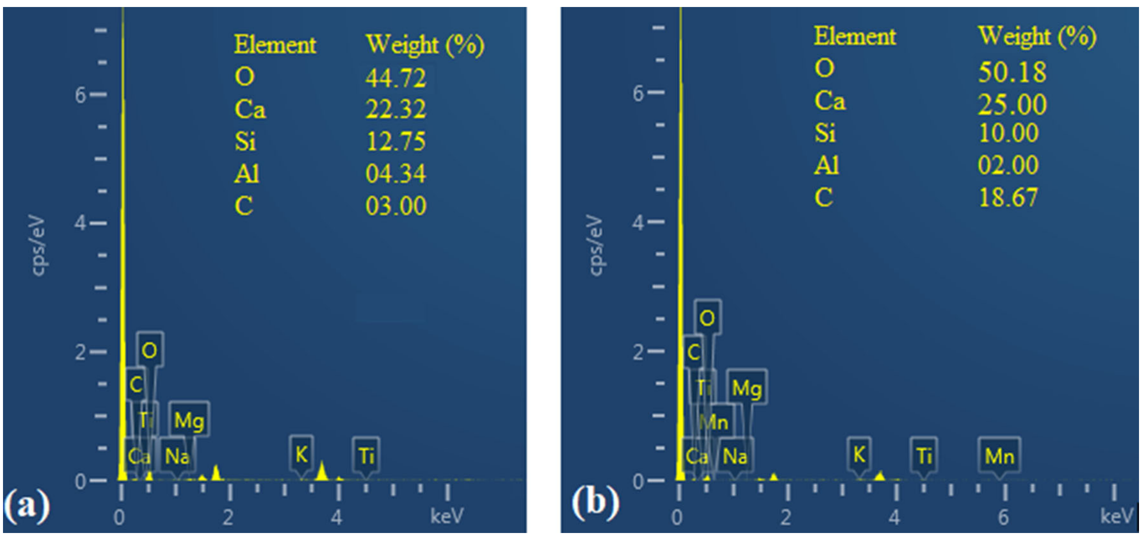

Fig. 5 EDX analysis: (**a**) UTRCCA; (**b**) CRCCA

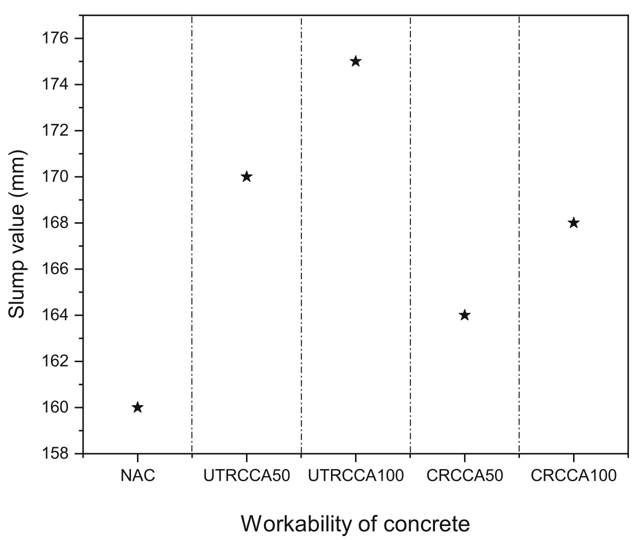

Fig. 6 Workability of concrete

UTRCCA100 were observed as 170 and 175 mm, respectively. After the carbonation treatment, the slump value of CRCCA50 and CRCCA100 was enhanced compared to the concrete mix with untreated RCCA. The slump values of CRCCA50 and CRCCA100 were 164 and 168 mm. Similarly, the water absorption and density of concrete having carbonated aggregate CRCCA50 and CRCCA100 also enhanced in relation to UTRCCA50 and UTRCCA100. The water absorption of CRCCA50 and CRCCA100 was found to be 2.9 and 3%, almost 21 and 26% less compared to UTRCCA 50 and UTRCCA100, respectively. The observations of water absorption and concrete density can be seen in Figs. 7 and 8, respectively. Also, adding alccofine to concrete has confirmed improved water absorption and percentage voids (Jindal et al. 2017). The free water in the mix increased due to the higher water absorption property of untreated RCCA, leading to a higher slump value. The characteristics of carbonated RCCA were enhanced due to $CaCO_3$ developed during the carbonation

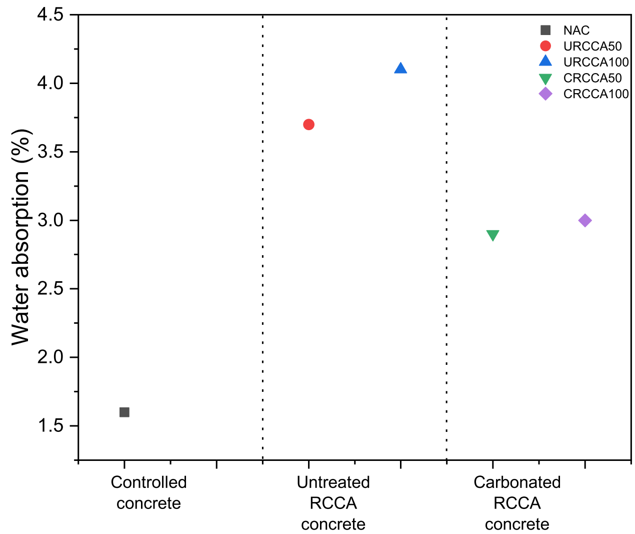

Fig. 7 Water absorption of concrete

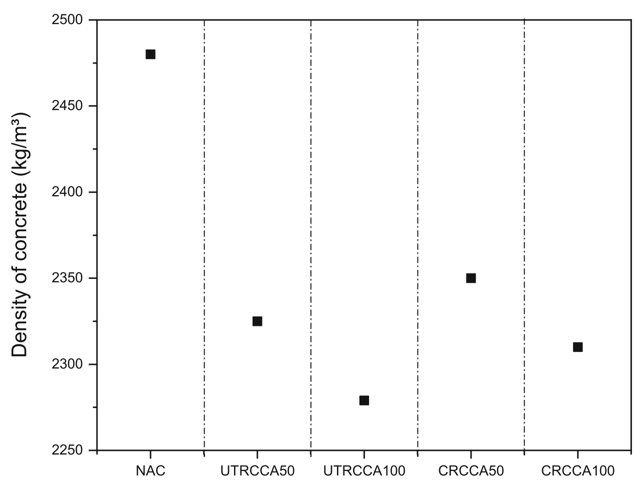

Fig. 8 Density of concrete

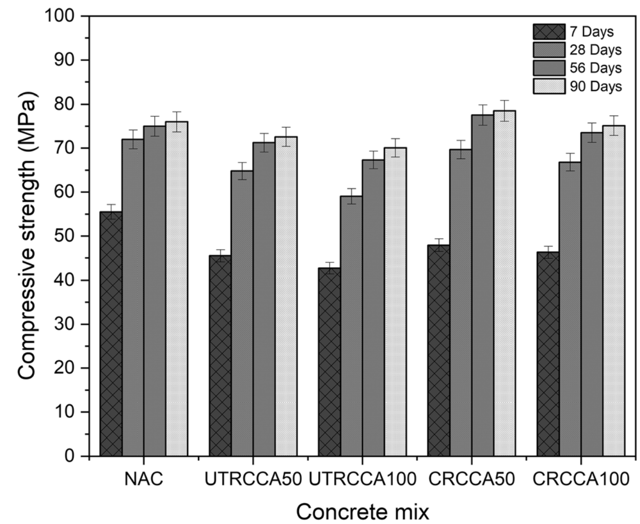

Fig. 9 Compressive strength of concrete

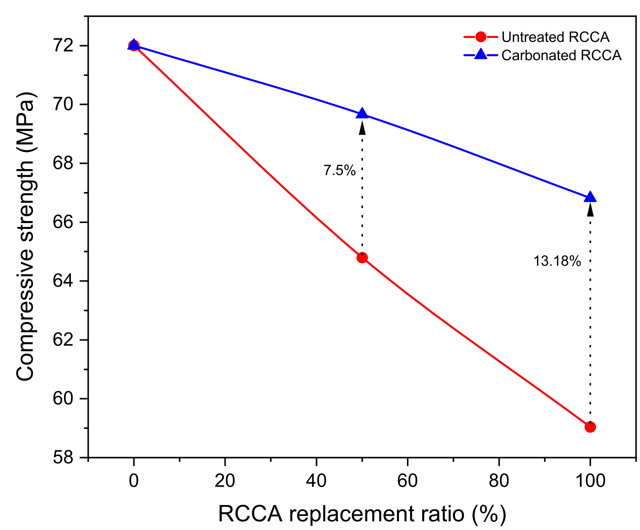

Fig. 10 Effect of coarse aggregate replacement ratio on 28 days compressive strength of concrete

treatment. Also, the characteristics of the concrete mix were improved due to ultra-fine pozzolanic alccofine particles, which improved the concrete's porosity, workability, density, and water absorption characteristics.

The 7, 28, 56, and 90 days compressive strength of concrete comprising NCA, untreated RCCA, and carbonated RCCA can be understood through Fig. 9. The 28 days compressive strength of UTRCCA50 and UTRCCA100 was found to be 64.8 and 59 MPa, respectively, 10 and 18% inferior relative to NAC. However, the compressive strength of carbonated RCCA concrete has improved in comparison with concrete with untreated RCCA. The 28 days compressive strength of CRCCA50 and CRCCA100 was found to be 69.7 and 66.8 MPa which are 7.5 and 13% superior compared to UTRCCA50 and UTRCCA100, respectively. The compressive strength of concrete decreased with the rise in the percentage replacement of coarse aggregate, as presented in Fig. 10. Instead, the 90 days compressive strength of UTRAC50 and UTRCCA100 was found to be even better and nearly equal to the NAC, which proves that the carbonation treatment of RCCA and the existence of alccofine can effectively enhance the characteristics of RCCA concrete.

3.3 Environmental aspects

Using raw materials from natural resources for manufacturing concrete has given birth to many environmental complications, like exploitation of non-renewable natural resources, carbon dioxide emission, and energy utilization. The replacement and utilization of RCCA in place of NA can solve these environmental concerns effectively. It has been stated that the 100% replacement of RCCA in place of NA to produce 1 m^3 of concrete can save about 43.8% of natural resources (Ding et al. 2016). About 32 kg CO_2 equivalent greenhouse gases (GHGs) are emitted to produce one ton of NA, whereas while producing one ton of recycled coarse aggregate, only 11 kg CO_2 equivalent GHGs are emitted. The manufacture of RA in place of NA has a 38%, 30%, 66%, and 57% less impact on humanoid healthiness, ecosystem quality, weather change, and resources, respectively (Hossain et al. 2016). Contradictory, due to the inferior properties of RCCA, utilizing a higher percentage of RCCA in replacement to NA in concrete requires supplementary cement content (Marinković et al. 2010; Xiao and Ding 2013). Moreover, cement, out of all the concrete raw materials, plays a significant role in the emission of GHGs (Jiménez et al. 2018). Instead, carbonation treatment of RA can be utilized for consuming CO_2 from the environment. Carbonation treatment of aggregate can significantly improve the properties of concrete without using any additional amount of cement. Due to the cementitious properties of alccofine, adding alccofine can further reduce the amount of cement to be used. As per a study, 11 kg of CO_2 can be absorbed by one ton of recycled crushed stone (Kikuchi and Kuroda 2011). Similarly, after carbonation treatment of RCCA, one ton of RCCA can absorb about 7.9 kg of CO_2 (Xuan et al. 2016). During the carbonation treatment, the CO_2 gets converted into a stable compound that is $CaCO_3$, so there will not be any leakage problem (Peter et al. 2008). Contradictory to other RCCA treatment techniques, carbonation treatment of RCCA can easily be implemented at an industrial level. The CO_2 content in the cement and power station plant emissions is about 12–30% (Romano et al. 2013). The RCCA can easily be piled somewhere near to the industry in such a way that emissions from the industry flows through the RCCA, the RCCA will absorb the CO_2 from the emission reducing the GHG's from the atmosphere.

Hence, the utilization of carbonated RCCA and alccofine for the development of concrete can not only improve the characteristics of RCCA concrete but also reduce the negative impact on the environment.

4 Discussion

As previously discussed, RCCA exhibits inferior physical characteristics such as water absorption, crushing value, and bulk density compared to NA. Similarly, upon analyzing the microstructure (as depicted in Fig. 4), clear evidence of cracks and loose material can be observed in RCCA, while a more compact microstructure is evident in CRCCA. The application of carbonation treatment has been proven to improve the physical properties of RCCA. The increase in weight of CRCCA compared to RCCA is due to the development of $CaCO_3$ and silica gel. The improvement in the physical properties of CRCCA may be attributed to the carbonation treatment process, during which C–H and C–S–H hydration products react with the CO_2 to generate $CaCO_3$. The deposition of $CaCO_3$ on the surface and within the pores of the RCCA enhances both the water absorption and density of the aggregate. The deposition of $CaCO_3$ on the surface of RCCA reduces the effective pore and crack on the surface, subsequently hindering the infiltration of CO_2 and reducing the development of $CaCO_3$ in these voids. Consequently, as evidenced by the findings above, the enhancement in density is less in contrast to the enhancement in the water absorption of CRCCA. Additionally, since the $CaCO_3$ exhibits higher microhardness compared to hydration products, the crushing value of the RCCA is also enhanced (Dang et al. 2018; Iwase and Mori 2020; Lu et al. 2022). The concrete containing CRCCA also showed superior performance in comparison with untreated RCCA concrete. There are possibly two explanations for the enhancement observed in carbonated RCCA concrete. Firstly, the carbonation treatment can enhance the interfacial transition zone (ITZ) of RCCA, which in turn boosts the characteristics and microstructure of RCCA. This improvement in ITZ and microhardness subsequently enhances compressive strength characteristics in CRCCA concrete (Yildirim et al. 2015). Furthermore, the reaction between $CaCO_3$ and alumina from alccofine results in the formation of hemi-carboaluminate hydrate and mono-carboaluminate hydrate (Lu et al. 2019). Studies have also proven that the hemi-carboaluminate has converted to mono-carboaluminate at later ages, which may be the cause for the improved strength of CRCCA50 and CRCCA100 at 90 days (Liu and Yan 2008; Ipavec et al. 2011). Secondly, the ultra-fine particles of alccofine fill the pores in RCCA and RCCA concrete, improving the ITZ and bond strength among RA and cement paste (Kou et al. 2011). Also, the calcium hydroxide in old and new mortar reacts with mineral admixture to procedure C–H–S, enhancing the mix's strength characteristics (Shi et al. 2016). The favorable chemical composition of alccofine contributes to enhancement in hydration reactions, thereby improving the strength characteristics of the mixture. However, the disadvantage of using alccofine can be the significant hydration activity of alccofine which results in higher heat generation during hydration and accelerates the initial setting of the mix. Consequently, the increased temperature in the mix might contribute to autogenous shrinkage, a pre-existing concern, particularly in high-strength concrete, which increases the vulnerability to potential issues like cracking and reduced strength.

5 Conclusion

The research study investigated the development of eco-friendly RAC using carbonation treatment and alccofine. The construction industry's significant contribution to waste generation and resource depletion prompted the exploration of sustainable solutions. Replacement of NA with RCCA offers potential, but its mechanical and durability properties are often inferior to NA. To overcome the limitations of RCCA, carbonation treatment and the addition of alccofine were studied to enhance RCCA concrete's properties. Based on the outcomes of the study, the below conclusions were formulated:

- Carbonation treatment significantly enhanced the physical characteristics of RCCA when compared to untreated RCCA, through the deposition of $CaCO_3$ on the RCCA surface and within its pores. This treatment resulted in notable improvements in bulk density, water absorption, and crushing value of carbonated RCCA.
- SEM and EDX analysis unveiled the formation of $CaCO_3$ and silica gel during the carbonation treatment, leading to considerable enhancements in various physical properties of CRCCA compared to RCCA.
- Concrete incorporating carbonated RCCA exhibited superior workability when compared to concrete incorporating untreated RCCA. The workability of the CRCCA100 concrete mix closely resembled that of natural aggregate concrete.
- The enhancement of the ITZ of RCCA during carbonation treatment led to improved density and reduced water absorption properties in concrete made with carbonated RCCA compared to concrete using untreated RCCA.
- The compressive strength of concrete incorporating carbonated RCCA surpassed that of untreated RCCA concrete. At both 28 and 90 days, the compressive strength of concrete containing carbonated RCCA closely approached that of natural aggregate concrete.
- The complete substitution of NA with RCCA yields substantial advantages, as replacing one ton of NA with RCCA can result in a reduction in up to 21 kg of CO_2 − equivalent greenhouse gas emissions during the production process. Notably, each metric ton of RCCA has the capacity to capture approximately 7.9–11 kg of CO_2, thereby facilitating the development of low-carbon concrete.

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